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LCA modelling for Zero Emission Neighbourhoods in early stage planning

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ABSTRACT

The building sector is a major driver of climate change, and the increased focus on significantly reducing greenhouse gas (GHG) emissions in recent years calls for major initiatives in the way we plan, build and operate buildings and neighbourhoods. Life-cycle assessment (LCA) is a commonly used and well-established tool to estimate the total emissions caused by buildings throughout their entire life cycle. Yet, LCAs of more complex systems such as neighbourhoods are scarce.

We have developed an LCA model for neighbourhoods with a focus on GHG emissions based on a modular structure with five physical elements: buildings, mobility, open spaces, networks and on-site energy infrastructure. We applied it on the Zero Village Bergen pilot project in Norway.

The results give total GHG emissions of 117 ktons CO_2-eq over 60 years, equivalent to 1.5 tons CO_2-eq/capita/year or 21.2 kg CO_2-eq/m^2/year on average over the period. The buildings constitute the largest share of emissions among the elements with 52%, then mobility with 40%, and only 2.3% from networks and open spaces. Emissions embodied in the materials consumed in all the elements of the neighbourhood account for as much as 56% of total emissions, with a large share coming from materials consumed in mobility vehicles. Critical parameters are emission intensities for electricity and heat production by waste incineration, as well as the daily distance travelled by the inhabitants.

1. Introduction

The 2015 Paris agreement of an average global temperature rise of maximum 2° compared with pre-industrial times has led to a growing focus on climate change. The building sector is a major source, accounting for about one third of both energy consumption and greenhouse gas (GHG) emissions globally [1]. With the aim of reducing energy use in buildings through country-level regulation, the EU has established two legislative directives: the Energy Performance of Buildings Directive (EPBD) [2] and the Energy Efficiency Directive [3,4]. This has motivated research, new building codes and the development of concepts that provide guidance for high energy efficiency in buildings. In Norway, the Research Centre on Zero Emission Buildings (ZEB Centre) was named a research centre of excellence from 2009 to 2017, with a vision to eliminate the GHG emissions caused by buildings. Its main objective was to develop competitive products and solutions for existing and new buildings leading to a market penetration of buildings that have zero emission of GHGs related to their production, operation and demolition [5]. In 2018, the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre) was started as a follow-up to the ZEB Centre, envisioning 'Sustainable neighbourhoods with zero GHG emissions' and with a goal to develop solutions for future buildings and neighbourhoods with no GHG emissions, thereby contributing to a low carbon society [6]. With this expansion in scope, the ZEN Centre researchers already acknowledge that many additional questions and challenges have arisen. However, it is less obvious what the good choices are and how to use LCA for decision-making support at the neighbourhood level, e.g. regarding functional unit(s), system boundaries and assumed input values for critical variables and parameters. In particular, this will have to be much better understood in the early stage planning process of ZEN projects, where LCA should play a role in the decision-making. Unfortunately, the research literature is scarce in this area at present.

1.1. Environmental assessment of buildings

Knowing what factors drive emissions and impacts over the entire life span of a building is essential to achieve significant environmental improvements in the building stock. For this purpose, life cycle assessment (LCA) is a common and well-established tool [7–9]. LCA systematically addresses the environmental impacts of a system through its life cycle stages, from raw material acquisition, through energy and

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material production, to use and end-of-life treatment [10]. LCA studies at the building level have led to valuable insights that can now pave the way for emission reductions in the building sector [11,12].

One important finding is how the relative importance of emissions from the operation of the individual building (heating, cooling, lighting, ventilation and appliances) compared to the emissions embodied in materials used in the building have changed over time, as a consequence of improved technology and new building codes. Historically, results have shown the dominating role of the use stage, which traditionally accounts for some 80–90% of total emissions [11,13,14]. However, more recent studies have concluded that especially when buildings with low energy consumption are evaluated, such as in low-energy or passive-house designs, the share of embodied emissions from materials is considerable [15–19] [19]. found that the embodied emissions over the life-cycle of the building accounted for as much as 55–87% of the total GHG emissions for Norwegian ZEB case studies examined by the ZEB Centre.

When focusing on the other stages of the life cycle, previous research indicates that 2–15% of the emissions are driven by the construction stage [19–21] [21]. however, found that among all the life cycle stages, the construction and demolition stages together represented less than 1% of the total carbon emissions for a residential building in China.

Other lessons learnt from LCA on buildings are related to the use of alternative and renewable materials, different architectural design options (such as shape, envelope and passive heating and cooling systems), user behaviour, the potential of energy-positive buildings and the associated consequences of a greater exchange of self-produced energy to external grids [22–26].

1.2. From buildings to neighbourhoods

In recent years, the focus has shifted from studying individual buildings treated as objects independent of the surrounding environment, to considering stocks of buildings and larger systems such as cities or neighbourhoods [27–29]. Still, the LCA literature at the neighbourhood level is scarce and highly influenced by the complexity and context dependency of the systems studied, which leads to heterogeneous approaches in how LCA modelling is done [18,28].

The choice of system boundaries is a factor that stands out from previous research, and is shown to have considerable impact on the results. The boundaries define what to include in the analysis, both regarding different life cycle stages and various physical elements in a neighbourhood, such as buildings, mobility, open spaces and infrastructure. Some research concentrates on clusters of buildings [30,31], while others also consider the users' mobility [27,32–34]. The most complex LCA studies include both buildings, mobility and other elements like open spaces and networks [25,35,36]. The life cycle stages considered also vary, from only looking at the use stage, to also considering the production and end-of-life stages [18,28]. Such different choices of system boundaries clearly lead to difficulties in comparing results from LCA studies. Nevertheless, some important take-away messages are worth noting.

When focusing on the physical elements, the daily mobility of inhabitants seems to have a considerable impact on total emissions [32]. found that user transportation contributed to 51–57% of the total GHG emissions, when including the materials consumed in constructing the buildings, in replacements in the use stage, and transportation in the analysis [25]. found that transportation constituted a considerable share of the impacts, with 44–47% of the total use stage emissions. Studies that also include the manufacturing of the modes of transport are lacking, with a few exceptions [36]: found that indirect emissions (including, among other things, vehicle manufacturing and building roads) constituted 52% of the total emissions from transportation [27]. found the same share to be 22–27%, depending on the location of the neighbourhood (city centre, periphery or district).

The large contributions and difference in results from these studies indicate that much more research is required on indirect impacts from mobility related to ZENs. Fortunately, these issues are already making their way into standards, such as the new Norwegian standard NS 3720 Method for GHG calculations for buildings [37], which expands the system boundaries compared to the standard EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method [38], by including transport in the use stage as a new module (B8) in calculations of GHG emissions from buildings; see S1 in the supplementary material.

Temporal aspects and assumptions about the future are often crucial when conducting an LCA, and in particular, the long lifespan of the physical elements of a neighbourhood makes forecasting emissions difficult and subject to high uncertainty. This is highlighted in several studies, and key factors that drive this uncertainty are the future emission intensity of electricity (g CO_2-eq/kWh), future technologies in buildings, infrastructure and mobility, and the temporal distribution of environmental impacts [27,28,32,36,39]. Also, the forecasted climate change is expected to decrease heating energy use while at the same time increasing cooling energy use, leading to a net increase of energy use in the building sector [39,40]. However, in ZEN projects that involve highly energy-efficient buildings that consume only small amount of energy for heating and cooling, such a climate change effect will not be very large.

Furthermore, existing studies are usually conducted on existing neighbourhoods, cities or districts. However, the power of LCA is only fully utilized when it is also used as a tool in the early stage planning of new neighbourhood projects [41]. describe a tool called NEST (Neighbourhood Evaluation for Sustainable Territories), an LCA tool for assessing the environmental impact of urban projects, developed by Ref. [42]. By including the production, maintenance, use and end-of-life stages for both buildings and open spaces, as well as the daily mobility of the inhabitants, the tool makes it possible to look at different solutions for neighbourhood projects. The tool has been used in urban planning projects in France, and this holistic approach should be explored in neighbourhood projects elsewhere. It has also been an inspiration in this study.

More research is obviously required in the field of LCA at the neighbourhood level, and in particular for ZEN projects that are motivated by transitions to a low-carbon future. Such research is needed both on what life cycle stages and physical elements in the neighbourhood contribute significantly to different categories of environmental impact, and on the need for a broader knowledge of the critical factors that influence emissions and impact results in varying contexts. Such knowledge is fundamental and should serve as a foundation for the development of ZEN concepts.

1.3. Problem statement

The objective of the work in hand is to contribute to the expedient use of LCA of neighbourhoods at an early planning stage, by focusing on important contributors to and critical factors for climate change impacts. Through the development of a model tested for a ZEN project in the early planning stage located in Bergen, Norway, the following research questions are answered:

- What are the dominant physical elements and life cycle stages contributing to the total GHG emissions at neighbourhood scale?
- What are the critical factors that affect these contributions and what are their sensitivities?
- What are the strengths and weaknesses of the model that has been developed? Can it provide useful inputs to the early stage planning process of a ZEN project?

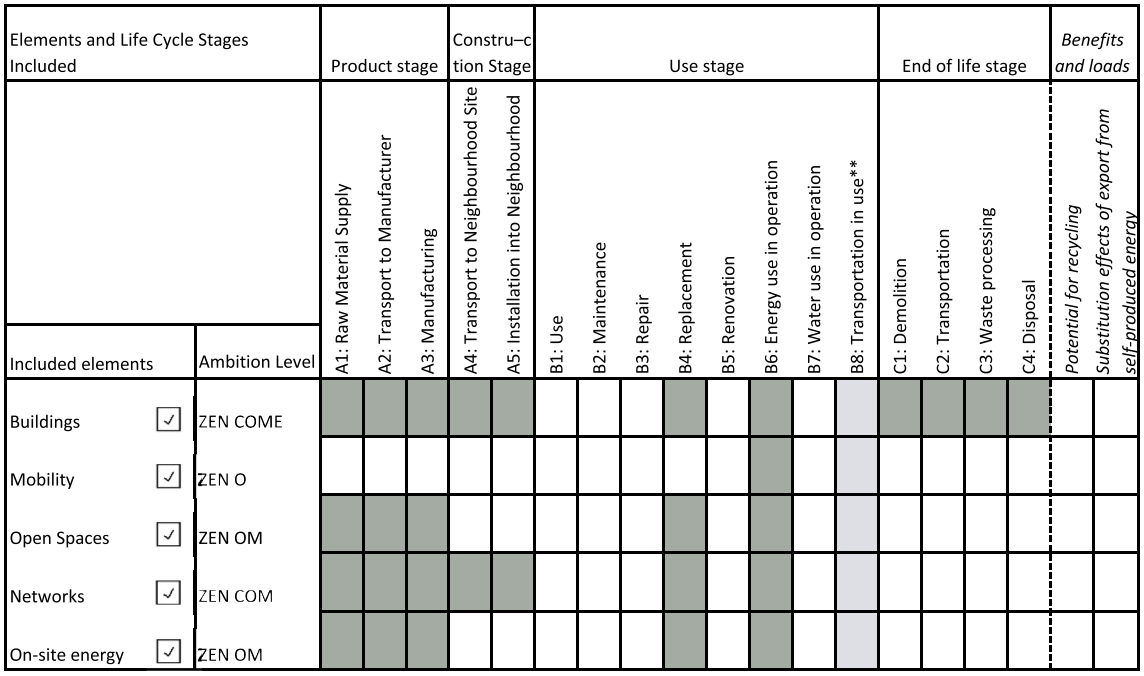

Fig. 1. Modular structure used as basis for LCA at neighbourhood level. Note: the elements and ambition levels marked in this figure are here randomly selected and serve only as an example of the use of the structure.

2. Material and methods

In this work, we developed a modular structure that serves as a basis for LCA with a focus on climate change at the neighbourhood level. Then, we applied it in a case study; called Zero Village Bergen (ZVB) located outside the city of Bergen in Norway, which is a ZEN pilot project for the ZEN Centre. The project is in the early planning stages with a presumed launch in 3–4 years. According to the present plans, it will be Norway's biggest zero emission project for buildings [43]. Although the model is adapted to the specific case, the methodology and calculation procedures are intended to be applicable to any other LCA study at neighbourhood level.

2.1. Modular structure

The modular structure of the LCA model is presented in Fig. 1 and consists of two dimensions to cover both the physical elements in the neighbourhood (buildings, mobility, open spaces, networks and on-site energy infrastructure), and the life cycle stage modules included in the LCA. The latter is described by ambition levels, and the different modules (A1-C4) are based on the new national standard NS 3720 [44]. Since mobility is defined as a separate element in the model, the transportation in use (B8, marked with grey in the figure) is excluded in the analysis of emissions from the 'buildings' element.

The zero emission ambition levels are based on a previous approach recommended by the ZEB Centre, called the 'ZEB Definition' [45]. It refers to the fact that a different number of life cycle modules from A1 to C4 – a few or many, depending on the ambition level determined by a given project owner – can be included in the zero emission ambition for each of the physical elements. The following description of these ambition levels is adapted from the ZEB definition.

- ZEN O: Emissions related to all operational energy "O", i.e. module B6 in Fig. 1.
- ZEN OM: Emissions related to all operational energy "O" plus all embodied emissions from materials "M.", i.e. modules A1-A3 and B4.
- ZEN COM: The same as OM, but also including emissions relating to the construction "C" stage, i.e. modules A4-A5.
- ZEN COME: The same as ZEN COM, but also including emissions relating to the end of life "E" stage, i.e. modules C1−C4.

For any given ZEN project, the elements and life cycle stages to include in the LCA analysis can be adjusted to match the policy choices of the project, or questions of interest for each LCA study. Hence, the modular structure of the model offers flexibility regarding varying scopes and objectives of a given study.

At the top left side of the structure, the emission intensity for electricity is stated (here it is chosen to be "Norwegian"). In Norway, the new standard NS 3720 on GHG calculations in buildings [44] recommends looking at two different scenarios for the future emission intensity of electricity – Scenario 1 (NO) and Scenario 2 (EU28 + NO) – based on the Norwegian and the European production mix, respectively. In practice, Scenario 1 considers Norway as an isolated electricity system without import/export of electricity, and Scenario 2 assumes that electricity is flowing freely between European countries, including Norway. These two scenarios must be regarded as extreme variants of the nationally consumed electricity mix, since each year includes both the import and export of electricity. Details on the emission intensities are given in S2.1, and Fig. 2 represents the two scenarios as they evolve from 2015 to 2080.

2.2. LCA model for Zero Village Bergen

An LCA model was developed for Zero Village Bergen (ZVB) using the modular structure presented in Section 2.1. For all the elements (buildings, mobility, open spaces, networks and on-site energy infrastructure), the "ZEN-OM" ambition level was applied in this study, including the production stage (A1-A3), as well as replacements (B4) and energy use in operation (B6).

An exception is for the networks, where the energy use in operation is excluded due to assumed very low emissions compared to the other elements. The modular structure adapted to the present study, as well as a map of the neighbourhood, is presented in S3 and S4 respectively. The analysis period is 60 years, equivalent with the assumed lifetime of buildings and infrastructure, and the focus in this study is on GHG

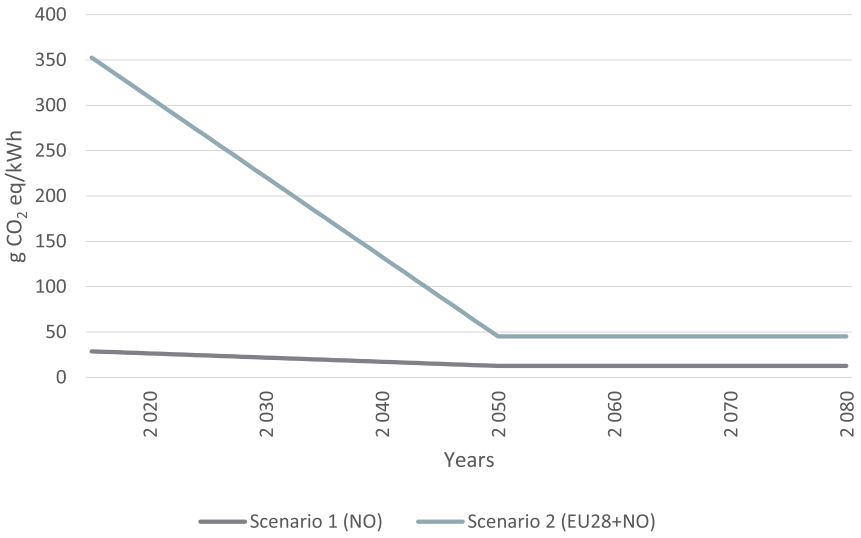

Fig. 2. Evolution of emission intensities for electricity (g CO_2-eq/kWh) 2015–2080 based on scenarios recommended in NS 3720 [44].

emissions associated with each of the elements throughout this period. At the current planning stage of the project, different energy system alternatives are under consideration, including joining the presently existing district heating system in Bergen, the use of a new local CHP plant, or the use of new ground source heat pumps [46]. We assumed that the heat demand is covered by connecting to the district heating system, and that the electricity demand is supplied from the external power grid and with local production of electricity by photovoltaic panels. Regarding the emission intensity, scenario 1 (NO) was chosen for both import and export of electricity between the neighbourhood and the external power grid.

Aiming for the ZEN OM ambition level implies setting the waste system outside the system boundary. In the case of a neighbourhood covering its thermal load by district heating, fed partly by heat resulting from waste incineration as is the case in Bergen, the GHG emissions from waste incineration will be assigned to the energy use in the operation (B6) module. Also, because of the ongoing debate in Norway whether the emissions from waste incineration should be assigned to the waste producer (an inhabitant) or to the end-user of the waste (the district heating company), we consider both allocations method in a sensitivity analysis.

2.2.1. Buildings

The building stock in ZVB consists of residential and non-residential buildings, with a total area of 91 891 m^2 [47], see Table 1. There will be 695 dwellings and 1340 inhabitants, see S5.1. The estimated area for parking is based on information on the number of parking spots, see S5.2.

Table 1
Building stock and areas in Zero Emission Village Bergen (ZVB) [47]].

Building type	Floor area (m^2)
Terraced house	62 136
Apartment block	23 028
Total residential	85 164
Kindergarten	1061
Office	2833
Shop	2833
Underground parking	*21 657*
Total non-residential (excl. parking)	6727
Total ZVB (excl. parking)	91 891

2.2.1.1. Production and replacement stages. The emissions embodied in building materials, $E_{b,mat}$, come from the initial materials contained in the buildings, as well as the replacement of materials throughout the 60 years period, see Equation (1).

$$E_{b,\,mat} = \sum_{bt} \left\{ [(E_{mat,init})_{bt} \cdot A_{bt}] + \sum_{i=0}^{60} \left[(E_{mat,repl})_{i,bt} \cdot A_{bt} \right] \right\} \quad (1)$$

$E_{mat,\,init}$ represents the emissions embodied in the materials initially contained in the buildings (kg CO_2-eq/m^2), $E_{mat,\,repl}$ the emissions embodied in the materials used in replacements (kg CO_2-eq/m^2), *bt* the building type, *A* the area (m^2 floor area) and *i* the year.

Material lists are presented in S5.3. Because of limited access to detailed data and uncertainties in design choices in the early planning stages, all residential buildings were assumed to consist of the same amount of materials per unit of floor area. The same goes for the non-residential buildings (all the non-residential buildings considered are equal in materials to an office building). For residential buildings and parking garages the material lists were provided by SINTEF (research partner with the ZEN Centre), and for non-residential buildings, the materials list was based on the materials included in a pilot project for a ZEB office building performed by the ZEB Centre [48]. For both building types, the GHG emissions per amount of material were based on either relevant national EPDs or the Ecoinvent database. The replacements are based on the estimated service life of each material, and the emissions embodied in replacement materials (B4) are assumed equal to the ones in the initial product stage (A1-A3).

2.2.1.2. Energy use in operation. The energy use in the buildings is based on work performed by the ZEB Centre [47] where the buildings planned for the ZVB project were already estimated by IDA-ICI simulations. This gave a total thermal load of 3283 MWh and a total electric load of 3257 MWh per year, see S5.4. Fig. 3 shows the yearly load in kWh/m^2 for the different residential building types.

It is assumed that the loads are constant for all future years in the analysis period. While the electric load is covered by electricity, the thermal demand (for space heating and domestic hot water) is covered by connecting to the district heating network in Bergen. The emission intensity of the district heat is calculated based on the emission factors for the specific sources of energy. In Bergen, 87% of the energy comes

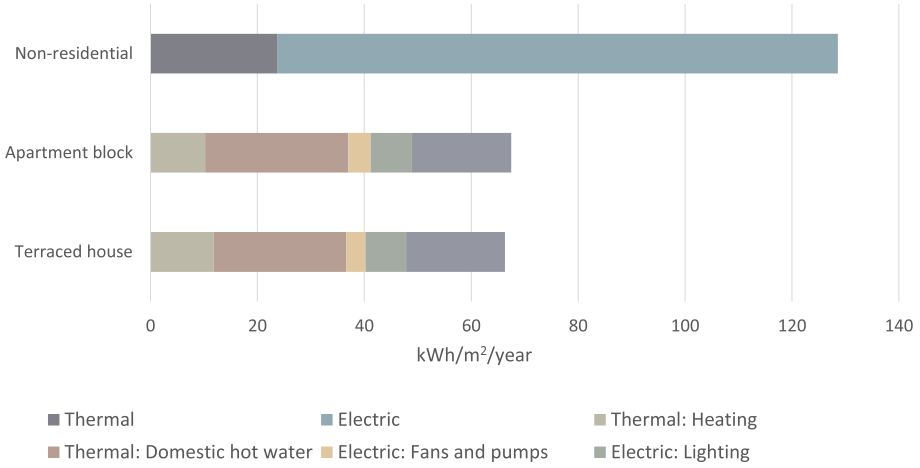

Fig. 3. Yearly energy load of residential buildings ZVB (in kWh/m2/year) (adopted from Ref. [47].

from waste incineration and the emission intensity of the district heat is assumed to be 163.2 g CO_2-eq/kWh in 2020, when emissions from waste incineration are allocated to the district heating production, see S2.2.

2.2.2. Mobility

Three means of transport are considered for the mobility in ZVB; personal vehicles, buses and light rail. Due to the extensive planning for public transport and cycling facilities [43], the distance travelled with each mobility type is based on statistics on travel habits for people with very good access to public transport, see S6.1.

Although the new Norwegian standard NS 3720 suggests including transportation of users, it does not specify a methodology for calculating the emissions for different means of transport. Nevertheless, the standard suggests using a project conducted by the Norwegian research institute Vestlandsforskning, completed in 2011, as a source for indicative emission factors for the current situation [44]. The documentation behind the results reveals large heterogeneity on data on energy use and emissions from different means of transport from previous research [49], but concludes with providing chosen estimates for several transportation modes intended for Norwegian conditions.

The future evolution of fuel types/energy carriers, together with technical improvements for vehicles and fuel chains, makes the forecast of emissions from transport a complex task. The NS 3720 standard emphasizes that development and technical improvements influenced by regulation and tax systems will lead to reduced emissions per distance driven during a buildings' service life, and that this should be taken into account through scenario assessment [44].

2.2.2.1. Evolution of vehicle stocks. The evolution of vehicle stocks is based on an "ultra-low emission policy scenario" developed by Ref. [50]. The scenario is based on targets compiled by the Norwegian transportation agencies, and the evolution of passenger cars and buses distributed among fuel types/energy carriers is forecasted from 2010 to 2050. In the present study, the situation is simplified to only consider four types of fuel/energy carriers: battery, hydrogen, diesel and gasoline, and the trend is assumed to continue towards 2080 (see Fig. 4). It is assumed that the use of light rail is all-electric throughout the entire period.

2.2.2.2. Product and replacement stages. The emissions embodied in the materials for mobility, $E_{m,mat}$, were calculated using Equation (2).

$$E_{m,\,mat} = \sum_{i=0}^{60} \sum_{tm} [(E_{mat})_{tm} \cdot L_{tot,tm,i}] \quad (2)$$

E_{mat} denotes the emissions from the production of different vehicle types (kg CO_2-eq/km), L_{tot} the total neighbourhood yearly travel length (km), *tm* the transport mode (e.g. personal vehicle diesel) and *i* the year.

The emissions from the product and replacement stages of the transportation are based on a study by Ref. [49]. Due to the continuous replacements of vehicles, the emissions are considered per distance driven (see S6.3) and do not distinguish between the initial material inputs (A1 – A3) and replacements (B4).

Emissions embodied in vehicles per unit of distance are assumed constant throughout the 60-year period, but the total emissions of the vehicle stock change with time due to the evolution of fuel/energy carrier types as described in Fig. 4.

2.2.2.3. Energy use in operation. Total emissions from the operation of mobility, $E_{m,oper}$, are calculated using Equation (3).

$$E_{m,\,oper} = \sum_{i=1}^{60} \sum_{tm} L_{tot,tm} \cdot WtW_{tm,i} \quad (3)$$

$L_{tot,tm}$ is the total neighbourhood yearly travel length (km/y) and $WtW_{tm,i}$ (kg CO_2-eq/km) the emissions per km driven by transport mode *tm* in year *i*.

The results from the study by Ref. [49] were used as a starting point in 2010, see S6.4. Improvements in the fuel intensities were based on a study performed by Ref. [51]; where scenarios for fuel intensities of new passenger cars were forecasted up to 2050, see S6.5. The well-to-wheel GHG emissions $WtW_{tm,i}$ from each of the transport modes *tm* at a given year *i* are calculated using Equation (4).

$$WtW_{tm,i} = Energy_{TtW,i} \cdot (I_{TtW} + I_{WtT}) \quad (4)$$

$Energy_{TtW}$ denotes the propulsion energy needed (MJ/vkm), I_{TtW} the tank-to-wheel or direct emission intensity (kg CO_2-eq/MJ) and I_{WtT} the well-to-tank emission intensity of the fuel cycle of the fuel/energy carrier (kg CO_2-eq/MJ). The latter are emissions associated with producing and transporting the fuel needed for the given energy in the propulsion of the vehicle. I_{WtT} and I_{TtW} are held constant, while the propulsion energy is assumed to change over the years. Fig. 5 shows the evolution in the WtW emissions in g CO_2-eq/passenger-km for the relevant modes of transport in snapshots for 2020, 2040, 2060 and 2080.

2.2.3. Open spaces

Included in the open spaces element are emissions embodied in roads (including bicycle lanes), sidewalks and outside parking, as well as emissions from the operation of public lighting.

2.2.3.1. Product and replacement stage. It is assumed that the road network in ZVB consists of two types of roads; (1) wide roads with two lanes and bicycle lanes on each side and (2) narrow roads without

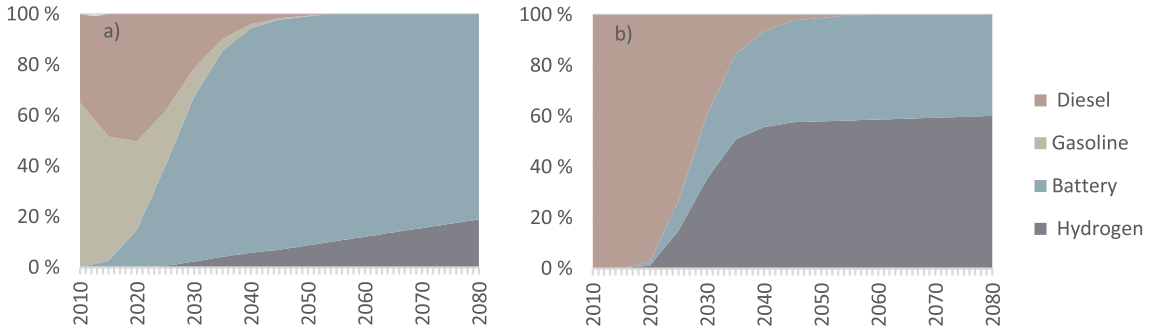

Fig. 4. Evolution of vehicle stock for a) passenger cars and b) buses by fuel type/energy carrier used in present study (See data in S6.2).

bicycle lanes. The road structure (materials and dimensions) is adopted from the work performed by Ref. [52]; see S7.1. The area of each of the sub-elements is roughly estimated based on the map of ZVB (S4), see Table 2.

The emissions from the materials in the open spaces elements are based on data from EPDs. Lifetimes of 20 and 40 years are assumed for the surface asphalt and base asphalt courses respectively and 60 years for the aggregates. S7.2 shows the materials included in the open spaces elements.

2.2.3.2. Energy use in operation. The emissions from the public lighting of open spaces in ZVB, $E_{o,oper}$, are calculated using Equation (5).

$$E_{o,oper} = \sum_{i=0}^{60} N \cdot P \cdot h \cdot I_{el,i} \quad (5)$$

N is the number of lighting units, P the power per unit (kW), h the hours with lighting per year and I_{el} the emission intensity for electricity (kg CO_2-eq/kWh) at year i. The number of hours the units are turned on is calculated using specific data for Bergen, see S7.3.

2.2.3.3. Networks. For all the alternative energy system solutions in ZVB (district heat, local CHP or ground source heat pump), a local thermal network will connect the buildings with the central energy network [46]. In the present study, this is the district heating network that connects ZVB to the already existing network in Bergen, see S8.1. The emissions embodied in the materials included in the part of this network that is geographically located inside the neighbourhood have therefore been incorporated, with components at the neighbourhood system level (but not at the building or dwelling level). The energy used to operate the network is not included.

2.2.3.4. Production and replacement stages. The length of pipes and the number of components units are a rough estimate based on the design of ZVB, resulting in 5000 m of new pipes (including both flow and return pipes) and one new pump. The amount of materials included is adopted from the study by Ref. [53]; where an LCA was carried out on a 100 m district heating system delivering energy to 240 dwellings by including the neighbourhood-, building- and dwelling pipeline systems. We assumed the average diameter of the pipelines to be 100 mm. The resulting material list and estimated service life for the pipes and the pump are presented in S8.2.

Table 2
Open spaces in Zero Emission Village Bergen (ZVB).

Open spaces element	Length (m)	Area (m^2)
Road type 1	3700	63 640
Road type 2	4400	49 280
Sidewalk	3700	11 100
Parking	–	2900

2.2.4. On-site energy

The on-site energy in ZVB consists of photovoltaic (PV) panels placed on the building roofs. The dimensions of the PV panels area and the generation of electricity are according to Ref. [47].

2.2.4.1. Production and replacements. The panels are placed on the available roof area of the buildings, with a total PV area of 22045 m^2 [47]. Emissions associated with the production of PV panels are found using Ecoinvent, see S9.1. The lifetime of the panels is assumed to be 30 years [54], and based on a suggestion from the ZEB Centre, a reduction of 50% of environmental impacts compared to the initial production due to technology development and efficiency improvements is applied to the replacement [45].

2.2.4.2. Energy use in operation. Based on available roof area,

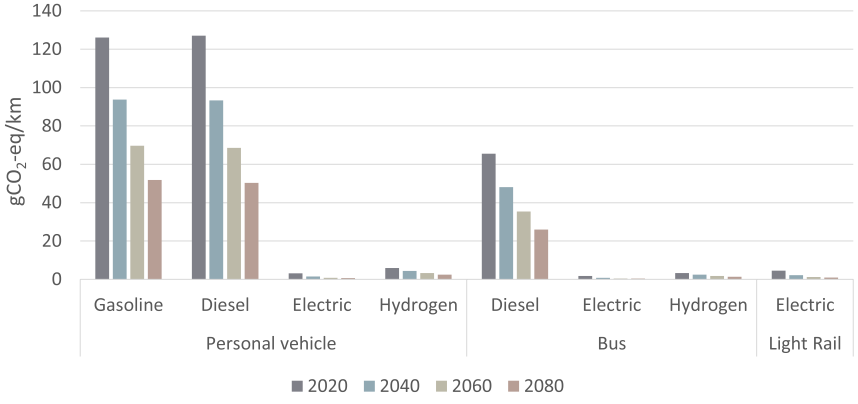

Fig. 5. Evolution of Well-to-Wheel (WtW) emissions from different modes of transport (see Table 15 in S6.5).

meteorological data, system efficiency and losses, and generation profiles, the yearly PV generation is estimated at 2941 MWh [47]. This local generation of electricity is assumed to generate so-called negative (i.e. avoided) emissions, since the PV panels cover some of the electricity demand of the buildings and are thereby assumed to reduce electricity use from the external power grid. The negative emissions associated with this generation are calculated using the emissions intensity for electricity (Scenario 1). The PV-generated electricity is either use within the neighbourhood or exported to the external electricity network.

2.3. Sensitivity analysis

To address the goal of investigating critical parameters in the LCA model, a sensitivity analysis was performed on selected factors that were expected to have considerable impact on the results and/or are associated with large uncertainties. All input parameters selected for sensitivity analysis were given a relative change in input value of +25%, and the sensitivity ratio (*SR*) was measured using Equation (6).

$$SR = \frac{\Delta R/R_0}{\Delta P/P_0} \quad (6)$$

$\Delta P/P_0$ represents the relative change in the input parameter and $\Delta R/R_0$ denotes the relative change in results. Hence, parameters with a high *SR* value have a high influence on results.

In addition to this, two different assumptions expected to have a great impact on the results were examined, namely the emission intensity for electricity and the allocation of emissions associated with waste incineration at the district heating central energy plant. For the latter, the alternative emission intensity for district heat was estimated at 16.1 g CO_2-eq/kWh, assuming significantly fewer emissions from the district heat compared to 163.2 g CO_2-eq/kWh as used in base case, see S2.2.

3. Results

3.1. General results

With the methodology described, the total emissions associated with the physical elements (buildings, mobility, open spaces, networks and on-site energy) and the life cycle stages (A1-A3, B4 and B6) resulted in a total of 117 ktons CO_2-eq over their lifetime. This equals 1.5 tons CO_2-eq/capita/year and 21.2 kg CO_2-eq/m^2/year, referring to the heated building floor area and as yearly average emissions over the 60-year analysis period. The emissions are distributed between the elements and life cycle stages as shown in Fig. 6. As indicated in the figure, the building element accounts for the majority of the emissions, amounting to approximately 52% of the total lifetime emissions. Mobility is the second greatest contributing element, responsible for 40% of the total emissions. The emissions from the networks and open spaces together constitute only 2.3%. Furthermore, it is worth noting the relatively low level of negative emissions from the on-site energy production that, using our assumptions, are actually less than the emissions associated with producing the photovoltaic panels.

The results show that the emissions from the product stage (pre-use, A1-A3) represent a significant share (24%) of the total emissions when all elements are considered. This does not include the product stage of vehicles in the mobility element; recall that thisis merged with the replacement stage of vehicles due to the shorter service life of vehicles.

The total emissions are distributed over the years as presented in Fig. 7. Emissions embodied in materials that are used for replacements for buildings, open spaces, networks and on-site energy (PV panels) are represented with emission peaks at certain points in time, while the emissions associated with the replacements of vehicles in the mobility element are distributed over the years (light green bars). These emissions slowly increase due to the shift from fossil fuel vehicles to battery– and hydrogen-based electrical vehicles.

When taking a closer look at the parameters leading to overall emissions, the two elements that account for the major part of the emissions - buildings and mobility - are reported in detail. For the mobility element, replacement of vehicles is the major emission source and production of personal vehicles account for as much as 96% of these emissions, see S10.1 and S10.2. While these emissions increase over the vehicles' lifetime due to the increased share of battery-based electric vehicles, the emissions associated with mobility operation decrease drastically for the same reason. In considering the total period of 60 years, the use of internal combustion engine vehicles (both personal vehicles and buses) dominates with 89% of the emissions, despite the assumption that these vehicles will be completely phased out by 2060, see S10.3.

When focusing on the buildings, the results reveal that energy use in operation accounts for the majority of the emissions at 59%. Of this amount, 91% is sourced from district heat for space heating and domestic hot water. Regarding materials, residential buildings obviously account for most of the emissions, given that 93% of the floor area in the neighbourhood is in residential buildings. This is amplified by the fact that residential buildings account for relatively more emissions when looking at emissions per floor area, see S10.4.

3.2. Results sensitivity analysis

The results of the sensitivity analysis are represented in Table 3 and reveal that the two parameters with the largest sensitivity ratio, and therefore with the largest influence on change in total emissions results, are the travel distance per inhabitant and the buildings' energy load.

Fig. 8 shows the change relative to the base case for each of the parameters and also for the two fundamental assumptions that are shown to have a considerable impact on the results, namely the emission intensity for electricity and the assumption of allocating emissions from waste incineration to the waste management system rather than to district heat production. If Scenario 2 (see Section 2.1) is used, referring to the EU28 + NO electricity production mix instead of the Norwegian electricity production mix, total emissions over the 60-year analysis period increases by 12.5%. This is despite the fact that negative emissions from the on-site electricity production will also be greater, due to the significant increase in emissions from electricity consumed in mobility. If the emissions from waste incineration are not allocated to the district heating production, total emissions decreased by 25.3%. Hence, this is one of the most critical assumption in the LCA model.

4. Discussion

This section discusses the modular structure presented in Section 2.1 and the model developed for ZVB described in Section 2.2. The results obtained from the model are discussed in the context of the research questions presented in Section 1.3, and critical factors and uncertainties are deliberated. Finally, the usefulness and limitations of the analysis are discussed, and further work required on the field of LCA modelling for ZENs is suggested.

4.1. LCA modelling on neighbourhood scale – results and critical parameters

When moving from individual buildings to the more complex system of a neighbourhood in LCA modelling, it is crucial to clearly understand the effect of the assumed preconditions, and of which physical elements and life cycle stages are included. The modular approach used in this study enables us to examine the effect of changing system boundaries, both as regards the included elements and life cycle stages and in presenting the results with several functional units. The modules make it possible to easily adjust the LCA to fit different ZEN projects, with different preconditions, and to compare different projects with different premises.

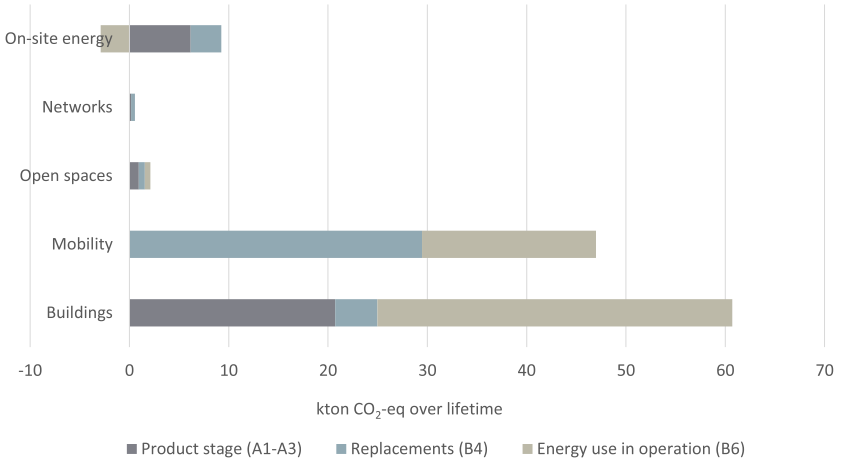

Fig. 6. Total emissions for ZVB distributed between elements and life cycle stages (see S10.1 for data).

The model developed for ZVB, as a case study based on the given modular structure, yielded results that offer useful insights. It revealed that buildings account for as much as 52% of the total emissions, given a ZEN OM ambition level for all physical elements in the neighbourhood. When looking at buildings alone, the emissions embodied in materials account for 41% of the total emissions, for the life cycle modules considered in the ZEN OM ambition level. This is comparable to, but not quite as much as, what was reported by Ref. [19]; who stated that the share of embodied emissions was between 55% and 87%. It should be noted that the emissions embodied in materials in the present study might be underestimates because of incomplete material lists for the residential buildings.

Another important finding is that of the remaining 59% of buildings emissions due to energy use, as much as 91% is associated with heat supply for space heating and domestic hot water. This again is mainly due to the single assumption that allocates the emissions associated with waste incineration to district heat production. In the present LCA, an emission intensity for heat production of 161.5 g CO_2/kWh based on criteria from the ZEB Centre [55] was used. Fig. 8 shows that if the emissions from waste incineration were not allocated to heat production, the total emissions would decrease by as much as 25.2%. Hence, a change in this parameter makes considerable impact on the total results. Whether or not the assumption used here is the correct one is debatable. On the one hand, it can be argued that heat is a by-product of waste incineration technology, the main purpose of which is thermal destruction of waste, and therefore emissions from the incineration process should be allocated to the waste management system. This is currently the allocation principle that is suggested in the new Norwegian standard NS 3720. On the other hand, as pointed out by Ref. [56]; '*waste is today an internationally tradable commodity that should be utilized where it gives maximum energy per unit greenhouse gas emitted*'. According to this view, emissions from waste incineration should clearly be allocated to heat production in a district heating system.

Something that may be surprising is that when Norwegian emission

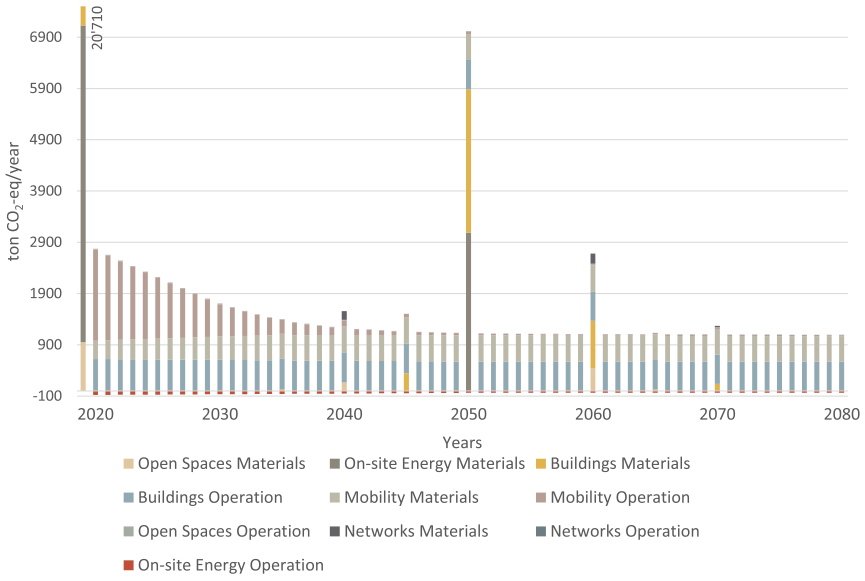

Fig. 7. Total emissions by year distributed by element and life cycle stage.

Table 3
Results sensitivity analysis selected parameters.

Sensitivity parameter	Sensitivity ratio	Change in total emissions result from base case
Emission intensity electricity +25%	0.021	0.5%
Emission intensity district heat +25%	0.279	7.0%
Travel distance/inhabitant/year +25%	0.403	10.1%
Emissions associated with vehicle production +25%	0.252	6.3%
Emissions embodied in building materials +25%	0.165	4.1%
Energy load (thermal and electric) +25%	0.306	7.7%
Area of PV panels +25%	0.055	1.4%
Energy public lightning +25%	0.005	0.1%

intensity is used, and assuming of symmetric weighting (i.e. using the same emission intensity for both directions of electricity exchanges between the power grid and the neighbourhood), the negative emissions "gained" from on-site production does not even cover the emissions embodied in the PV panels (see Fig. 6). Here, and also for several of the other elements, the choice of emission intensity for electricity becomes relevant. Similar to the intensity for district heat, this is also a much debated subject in LCA studies [57–59]. First of all, the future electricity mix is hard to predict. Further, the electricity network is a complex system with varying exchanges of energy between countries and continents that depend on the season, accessibility and propagation of transfer possibilities. The sensitivity ratio for the emission intensity of electricity indicates that a change in this parameter does not drastically affect the total result, see Table 3. This is the case when all emissions are accounted for, including negative emissions associated with the on-site production of electricity from PV panels. Because symmetric weighting is assumed, both the positive and negative emissions increase when changing the emission intensity. If negative emissions are disregarded, the total emissions from the neighbourhood, including all elements, would increase by 30% when changing from Scenario 1 (NO) to Scenario 2 (EU28 + NO). This clearly shows how critical this parameter is for the results. Due to the high sensitivity of the emission intensity of electricity, it is important to agree upon an emission intensity evolution over time, or an average value over the analysis period, that is as realistic as possible to facilitate decision making and choices of energy solutions for a ZEN project in the early planning stages.

The emissions from mobility in ZVB constitute 40% of the total neighbourhood emissions, and 37% of this comes from the operation of the transportation modes, i.e. the fuel/energy consumed in mobility. If the system boundaries are adjusted to match the ones examined by Ref. [32]; the results reveal large differences. While Bastos et al. found that transportation contributed 51–57% of the emissions when buildings (materials and operation) and transportation of the users were included, the comparable percentage was only 22% in the present study. This is probably partly because this study includes an optimistic future evolution in the share of electric personal vehicle stock combined with the low emission intensity for electricity. The remaining 63% of emissions from mobility come from the production of vehicles. If one adopts the system boundaries used by Ref. [27] that include buildings and mobility, the product stage for vehicles constitutes 27%, which is exactly the same as reported by Anderson et al. Their study, however, concludes that emissions from the operation stage constitute a larger share than vehicle production does, which may indicate that the percentages is a coincidence.

The open spaces element consisting of roads, sidewalks, outside parking, and public lighting, plus the network element including the district heating pipes, only constitute 2.3% of the total lifetime neighbourhood emissions. This number is expected to be higher for an as-built project, due to the possibility of underestimating amounts of materials included in the model, and a lack of detailed data. The low share still indicates a relatively small contribution compared to the building and mobility elements, which also indicates that open spaces elements may not have to be accounted for in the early stages of

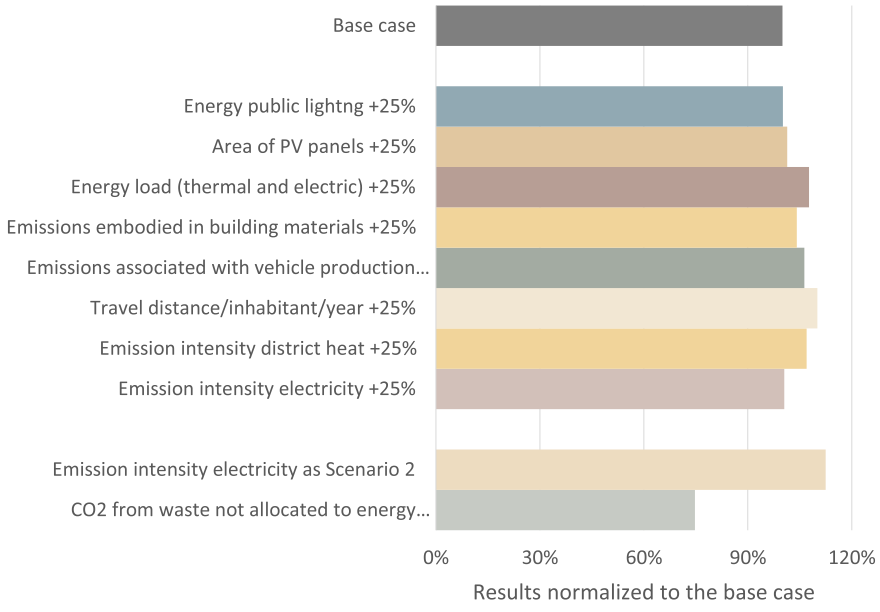

Fig. 8. Sensitivity analysis results relatively to the base case. Notice that the axis does not start at zero.

planning of a ZEN project.

Conducting an LCA in the early stages of planning a project is useful to gain knowledge that serves as basis for decision making. Some choices made in the early planning stages are crucial for the design of the project and will affect its environmental performance over the project's entire lifetime. Examples in this study include the choice of structural building materials, spatial planning designs and technologies in the energy system. Some choices are more difficult to control, such as the future evolution of the energy mix in the electricity and district heat supply system, and the evolution of technologies in the vehicle stock. However, it is possible to address these uncertainties by choosing a flexible energy system, such as waterborne heat systems in the buildings and by dimensioning the electricity network with local storage capacity to be able to meet a rapidly growing share of electrical vehicles. In practice, when conducting an LCA at an early stage of planning, the main focus should be on the decisions that can facilitate as the lowest possible emissions in the future. This study points to the importance of such possibilities that can reduce yearly emissions particularly during the next few decades.

4.2. Limitations and further work

Although the LCA model in this study offers several advantages in highlighting the dominant drivers related both to the physical elements and life cycle stages and facilitating for comparability between design choices and between projects, certain limitations do still weaken the model.

First of all, the model does not yet account for long-term changes in technology development and improvements in production processes for the replacement materials. The only exception is for the PV panels, where the emissions are assumed to decrease by 50% in the replacement. This limitation especially affects the accuracy of future mobility emissions, due to the frequent replacements of vehicles. With the current rapid technology improvement in the transportation sector, especially for electric vehicles, emissions from production processes will decrease, both for the vehicles themselves and for their fuel cycles. Further research is required to predict more accurate scenarios on future vehicle production. Emissions per distance driven for 2010 as reported by Ref. [49] and recommendations such as in the new NS 3720 standard [44] are not sufficient to make robust calculations on ZEN or other neighbourhood projects with an analysis period of 60 years. Also, the model does not consider the possible effect of climate changes on local climate. In Norway, the number of “warm days” ($< 20\,^{\circ}C$) is expected to triple by 2010, and the heating season is predicted to become shorter [60]. As discussed earlier, the effect of climate changes on emissions may not be significant compared to others emissions drivers, and is therefore of less relevance in early stages planning of ZEN projects.

Together with emissions associated with the replacement of materials (and vehicles), there are also significant uncertainties when it comes to the evolution of parameters such as emission intensities, the behaviour of inhabitants (travel habits, energy use, etc.) and the future distribution of different vehicle types. In order to make the model more complete and realistic, more research on alternative future evolution pathways is required.

When conducting an LCA, several environmental impact categories are commonly used to show a more holistic environmental performance profile of a product or process. However, this study only reports climate change measured in GHG equivalent emissions. A broader analysis is needed to avoid problem-shifting phenomena. For example, a set of technology choices in a given ZEN project yields reduced GHG emissions but increased environmental impacts in other impact categories such as acidification, land use change and photochemical smog. Therefore, the LCA model need to be extended to also consider other relevant impact categories, despite the fact that the present political focus is on energy use and GHG emissions.

Finally, the model is based on yearly values rather than hourly data for the consumption and production of energy. In practice, this means that the external electrical network is considered an infinite capacity battery and that it does not make any difference if the self-produced electricity is consumed locally in the neighbourhood or exported to the grid, or at what times during the year. This assumption can be justified by the fact that a symmetric weighting factor for electricity is used and that the emission intensity of electricity in Norway is fairly constant over the whole year. This is a simplification and may not reflect reality. Also, if the economic perspective is added, the price of imported vs. exported energy is commonly asymmetric. This perspective favours high self-consumption, because the price of exported energy is usually less than the price for import. Other factors such as energy storage and vehicle-to-grid concepts also become relevant here; however, they are outside the scope of this study.

5. Conclusion

In order to contribute to expedient use of LCA at the level of neighbourhood projects, and particularly in the context of several emerging ZEN projects, a modular structure that works as a basis for assessing ZEN projects at an early planning stage was proposed. An LCA model based on this structure was developed specifically for a ZEN project in Bergen, Norway. The goal was to determine the most important physical elements and life cycle stages contributing to the total GHG emissions of this project.

The results show that when considering the building, mobility, open spaces, network and on-site energy generation elements, as well as the three life cycle stages of the product stage, replacement stage and energy use in operation, buildings represent the majority (52%) of total GHG emissions, closely followed by mobility (40%). Among the life cycle stages, the total emissions are dominated by the emissions embodied in materials from the product stage and replacements (56%), with the remaining emissions resulting from energy use in operation (44%). For all the elements except for buildings, embodied emissions exceed the emissions from energy use. This is not the case for the buildings, mainly because of the emission intensity for district heat, where the emissions associated with incineration of waste are allocated to heat production. This assumption is therefore a critical factor, along with the value of the emission intensity for electricity, the daily travel distance per day for the inhabitants, and the emissions associated with vehicle production.

The LCA model has clear potential to facilitate decision making in early stages planning ZEN projects. It can provide information on dominant elements and life cycle stages, and its modular structure ensures comparability, transparency and adaptability. On the other hand, the LCA model, and consequently also its results, suffers from uncertainties and simplifications, particularly on how technologies, user behaviour and climate may change in a long-term perspective. Further work is therefore required when it comes to forecasting emission intensities, emissions associated with the production of materials and vehicles in the future, and the consequences of assuming symmetric weighting for emissions related to both directions of electricity exchanges between the power grid and the neighbourhood.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2018.12.034.

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